Assessment of Uncertainties in the C6.1 MODIS Cloud-Gap Filled Snow Products

Dorothy K Hall[1,2], George A. Riggs[3,2], Nicolo E. DiGirolamo[3,2] and Miguel Román[4]

[1]Earth System Science Interdisciplinary Center / University of Maryland, College Park, MD 20740
[2] Cryospheric Sciences Lab / NASA Goddard Space Flight Center, Greenbelt, MD 20771
[3]SSAI, Lanham, MD 20706
[4]Terrestrial Information Systems Lab / NASA Goddard Space Flight Center, Greenbelt, MD 20771

Reprocessing of the complete data record, Collection 6.1 (C6.1), will result in improvements in the MODIS cryosphere product suite. To address the need for a cloud-reduced or cloud-free daily snow product, there will be new products in C6.1 -- MOD10A1F (Terra) and MYD10A1F (Aqua) -- which are daily, 500-m resolution cloud-gap filled (CGF) snow-cover maps. Associated with the CGF maps is a cloud-persistence map showing the age of the snow (or other) observation in each pixel. Work is ongoing to evaluate and document uncertainties in the CGF snow-cover products. Results show that the CGF maps do an excellent job of capturing snow-cover build-up and depletion, especially in areas with cloud cover that is not continuous. The uncertainties in persistently-cloudy areas are currently being investigated. Comparisons between the Terra and Aqua CGF snow maps reveal differences that are related to differences in cloud masking, with the Terra snow maps being superior as validated in some areas in the western U.S. using NOAA meteorological-station data. The CGF data record will be extended through the Visible Infrared Imaging Radiometer Suite (VIIRS) era by creating a 500-m resolution Environmental Science Data Record (ESDR) of snow-cover extent using MODIS Terra and VIIRS snow maps.

MOD10A1F daily snow maps provide clear views of the surface

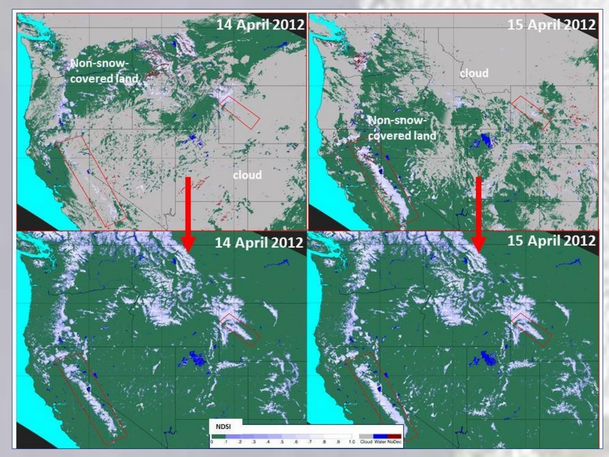


Figure 1. Examples of MOD10A1 and MOD10A1F snow maps in the western U.S. **Top row**: MOD10A1 snow maps with extensive cloud cover on 14 & 15 April 2012. **Bottom row**: MOD10A1F 'cloud-free' CGF maps corresponding to the MOD10A1 maps on the top row. Non-snow-covered land is green. Regions of interest (ROI) containing the Sierra Nevada Mts. in Calif. and Nevada (109,575 km^2) and the Wind River Range in Wyo. (22,171 km^2) are outlined in red.

Cloud persistence is tracked for each pixel

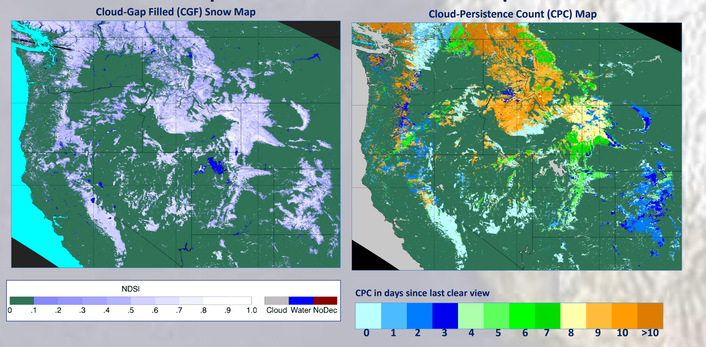
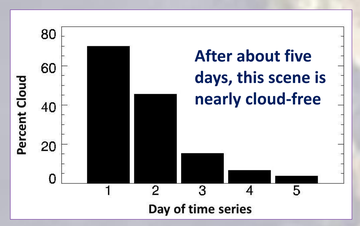


Figure 2. **Left** - Cloud-gap filled (CGF) MOD10A1F map for 19 March 2012. **Right** – Corresponding cloud-persistence count (CPC) map from the QA data layer, applied to only the snow cover. Each CGF map has a CPC map so that a user may determine the age of the snow observation for each pixel (Hall et al., 2010 & 2018; Riggs et al., 2018).

Figure 3. Bar graph showing percent cloud cover on a scene from the western U.S. (see location of the scene in Figs 1 & 2 covering six MODIS tiles). The percentage of cloud cover decreases dramatically in the first 3 – 5 days following the initiation of the gap-filling algorithm. In this example, the cloud cover drops from ~75 percent on Day 1 to ~4 percent on Day 5.



Absolute validation of MODIS CGF snow maps is often possible using NOAA meteorological station data

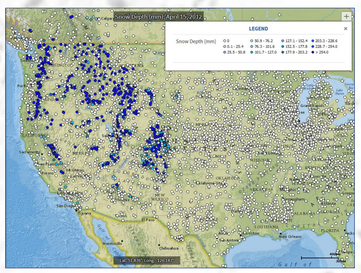
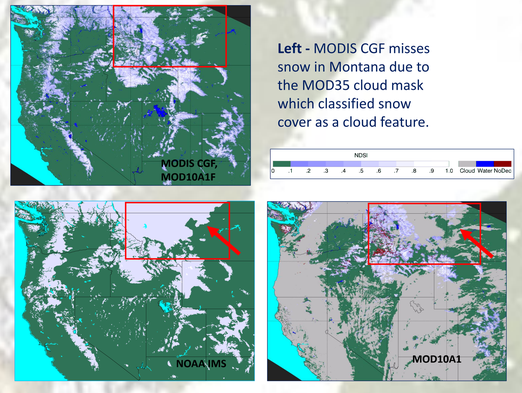


Figure 4. Snow depth (mm) from 15 April 2012 for the western U.S. Source: NOAA NCDC https://gis.ncdc.noaa.gov/maps/ncei/summaries/daily .

Comparison with other snow products, though useful, does not provide absolute validation because all satellite-derived snow maps have uncertainties



Left - MODIS CGF misses snow in Montana due to the MOD35 cloud mask which classified snow cover as a cloud feature.

Figure 5. Note the shape of the 'cloud' feature on this 25 March 2012 MOD10A1 snow map shown in the red rectangular area in the lower right snow map (see red arrow). The shape is similar to a snow feature shown in the NOAA IMS 4-km snow map (lower left). To investigate this further, the MOD35 cloud mask was removed (Riggs et al., 2018) revealing a feature that appears to be snow and not cloud (not shown). The determination that this is a snow feature was further confirmed by studying other satellite data and NOAA station data.

References

Gladkova, I., M. Grossberg, G. Bonev, P. Romanov and F. Shahriar, 2012: Increasing the accuracy of MODIS/Aqua snow product using quantitative image restoration technique, *IEEE Geoscience and Remote Sensing Letters* 9(4):740-743.

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Are both Terra and Aqua MODIS snow maps equally useful for development of an Environmental Science Data Record (ESDR)?

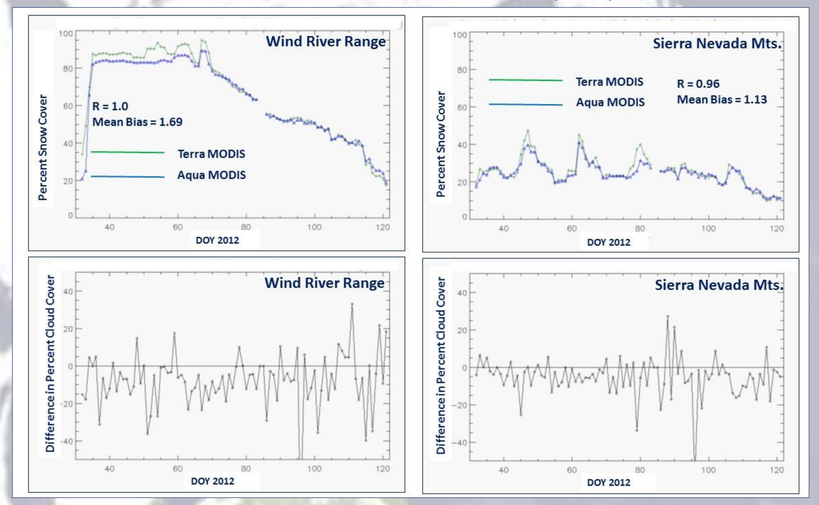
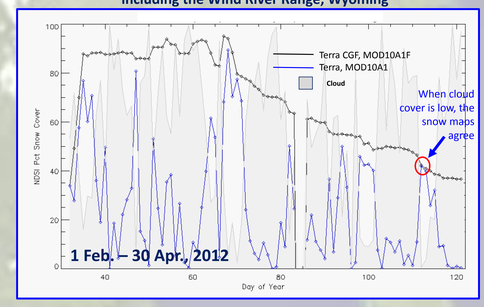


Figure 6. **Top row -** Time-series plots of percent snow cover in a 22,171 km^2 scene (see ROI that includes the Wind River Range, Wyoming, in Figure 1) and in a 109,575 km^2 scene (see ROI that includes the Sierra Nevada Mts., in Figure 1) using MODIS Terra and Aqua CGF snow-cover maps, extending from 1 February through 30 April 2012 (DOY 32 – 121). **Bottom row –** Difference in percent cloud cover by day for MODIS Terra minus Aqua for the Wind River Range and for the Sierra Nevada Mountains, corresponding to the top panels. "No-decision" pixels were excluded (not shown above). Aqua generally shows more cloud cover than does Terra. There are more 'no-decision' pixels on the Aqua MODIS snow map, most likely due to the inability of the Aqua MODIS cloud mask to classify large areas of cloud cover as 'certain cloud.' This shortcoming relates to the non-functional Band 6 detectors in the Aqua MODIS (see Gladcova et al., 2012 and Riggs et al., 2018 for further information). There are also some differences in the Terra and Aqua snow maps because cloud cover can be different due to the different overpass times. But the main difference in the Terra and Aqua snow maps is due to the need to use Band 7 in the Aqua cloud mask because of non-functioning detectors in Band 6 on the Aqua satellite.

MODIS CGF snow maps capture snow-cover patterns in areas with varying amounts of cloud cover

Comparison of Terra CGF and the standard Terra maps for an ROI including the Wind River Range, Wyoming



Comparison of Terra CGF and the NOAA IMS 4-km snow maps for an area including the Catskill Mts. in southeastern New York

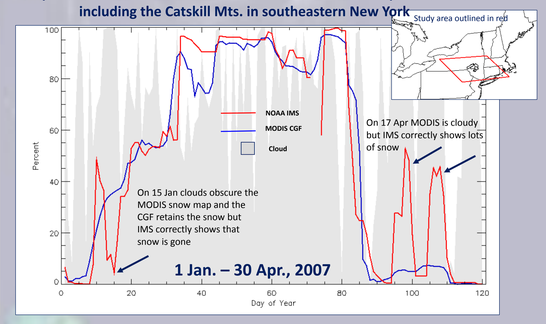


Figure 7. While both the ROI including the Wind River Range, Wyoming (left) (see Fig. 1 for location of ROI) and the ROI that includes the Catskill Mts., NY (red box on inset, right), have abundant winter cloud cover, the northeastern U.S. has more-persistent cloud cover. The MODIS CGF is able to capture the pattern of snow-cover accumulation and depletion, especially in the Wind River Range ROI. In the more-persistently cloudy northeastern U.S. ROI, snowfall from some snowstorms is missed due to persistent cloud cover that precludes snow on the ground from being mapped, as shown on the right when the Terra CGF maps are compared with the NOAA National Ice Center's 4-km IMS snow maps that provide daily, cloud-free snow cover.